

# Implications of Low Energy X-ray Emission from Millisecond Radio Pulsars

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## ABSTRACT.

Low energy X-ray emission (0.1-10 keV) from all six millisecond radio pulsars (MSPs) for which such emission has been reported support a proposed pulsar magnetic field evolution previously compared only to radiopulse data: old, very strongly spun-up neutron stars become mainly orthogonal rotators (magnetic dipole moment perpendicular to stellar spin) or aligned rotators. The neutron star properties which lead to such evolution are reviewed. Special consideration is given to agreement between predictions and observed X-ray emission for the aligned MSP candidate PSR J0437-4715.

## 1. Introduction

Properties of the radioemission from the most rapidly spinning disk population millisecond radio pulsars (MSPs) support the neutron star model-based expectation that these pulsars should be mainly orthogonal rotators or aligned rotators. There are three kinds of observational evidence for this.

1) A large fraction of the MSPs have two radio-subpulses of comparable strength separated in time by about half a period ( $P/2$ ), a signature property of an orthogonal rotator (Chen & Ruderman 1993, Jayawardhana & Grindlay 1996). In a sample of 8 of the fastest spinning disk-MSPs at least 4, and possibly 6, are in this category (Chen et al 1998); among canonical radiopulsars only a few percent are (Lyne & Manchester 1988).

2) The well studied original MSP, PSR 1937, is observed to have very different linear polarization properties in two narrow radio-subpulses an interval  $P/2$  apart, just as expected from the spin-up evolution of that pulsar into an orthogonal rotator whose dipole moment is on the neutron star's (NS's) spin-axis at the NS crust-core interface (CR 93).

3) At least one pulsar in the chosen MSP octet, PSR J0437-4715, and possibly several, have only a single very broad, structured radiopulse. Its pulse-width is so large ( $\sim 270^\circ = 3P/4$ ) that a plausible description of the observed radiation beam seems to require an almost aligned beam (and dipole moment) observed from a line-of-sight direction near that of the NS's spin-axis (Gil & Krawczyk 97). Because an almost spin-aligned radiobeam from a spinning NS sweeps out a smaller solid angle on the sky than that same beam would from an orthogonal rotator, one observation of an aligned MSP out of the 8 in the sample indicates a very considerably larger aligned fraction.

In Section 2 we consider the significance of MSP low energy X-ray light-curves when these data are combined with those from the same MSPs' radiopulses. Section 3 summarizes relevant NS model predictions from stellar magnetic field evolution as these stars were spun-up to become MSPs. Section 4 presents model predictions for an aligned MSP's thermal X-ray emission areas and compares them to those inferred from PSR J0437 observations. In no case is there a conflict between what is expected from special properties of NSs and what is observed.

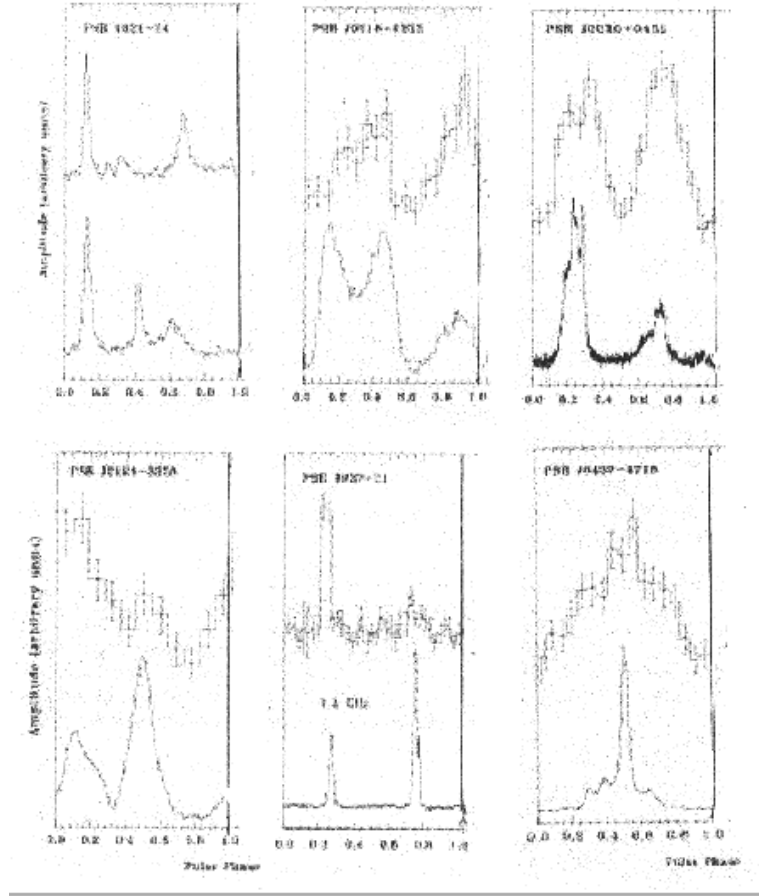


Fig. 1. Low energy X-ray light curves for the six radio MSPs for which such X-ray emission has been reported (Becker & Aschenbach 2002). Radio profiles are shown below the X-ray ones. The phase alignments between the X-ray and radio profiles have been arbitrarily fitted for PSRs J0030 and J2124.

## 2. X-ray and radio light curves

Low energy (0.1-10 keV) x-ray emission has been reported from 6 MSPs previously identified by their pulsed radioemission. The 6 X-ray and radio light curves are shown in Figure 1 (Becker and Aschenbach 2002). The upper curves show those for X-ray emission, the lower ones for radioemission. There is no significant difference between the radio and x-ray profiles except possibly in PSR 0218 (Fig.1 upper middle) and PSR 1821 (Fig.1 upper left). In those two MSPs the X-ray light curves seem to resolve an ambiguity: their radioemission light curve profiles contain a sub-peak structure from the double crossing of a hollow cone beam rather than emission from three truly separate beams. Among the 6 MSPs of Figure 1, five reinforce support for the orthogonal rotator interpretation suggested by the radio light curves. One, PSR J0437, clearly does not. However, its single very broad X-ray light curve does not contradict the nearly aligned rotator interpretation for it. Why observed X-ray emission from a hot polar cap can be so strongly phase-modulated even though the observer's line-of-sight is near the spin axis is discussed in CRZ 98.

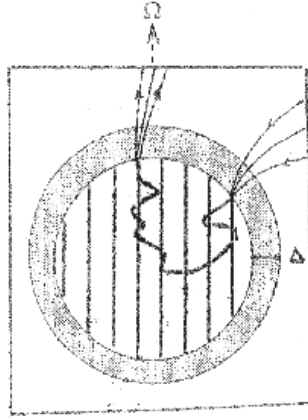


Fig. 2. Interior of a magnetized neutron star with a crust thickness  $\Delta$  (not to scale). The vertical bars symbolize quantized superfluid neutron vortex lines. Only a single core magnetic flux-tube is indicated.

### 3. Neutron star spin-up driven magnetic flux squeezing

We consider next why MSP genesis based upon very prolonged spin-up of older NSs with initially nearly canonical dipole moments can lead to much weaker dipole moments and, preferentially, to orthogonal or aligned rotators. Soon after its birth a canonical NS is well described (except, possibly, for a small central region) as an almost uniformly rotating fluid core (radius  $R = 10$  km) of neutrons ( $n$ ) together with protons ( $p$ ) and electrons several percent as abundant. This core is surrounded by a thin solid crust of thickness  $\Delta \sim 1$  km. Early in its life (age  $< 10^3$  years) the core will have cooled sufficiently that its neutrons become superfluid (SF- $n$ ) and its protons superconducting (SC- $p$ ). A core of SF- $n$  cannot rotate uniformly. Instead, the nearly uniform vorticity of  $4\pi/P$  in a rotating normal fluid fragments into a very dense almost parallel array of quantized vortex lines. The SF- $n$  vortex number density (per unit area)

$$n_V = \frac{2\Omega m_n}{\pi\hbar} \sim \frac{2 \cdot 10^4}{P(\text{sec})} \text{ cm}^{-2} \quad (1)$$

These vortices are represented by the eight straight vertical lines in the Figure 2 cartoon representation of a NS interior. As the NS spins-up (down) they remain parallel as they move in (out) toward (away from) the NS spin axis to maintain the vortex line density of Equation 1. The required addition (depletion) in total number of vortex lines needed for this comes from the creation (disappearance) of zero length vortex lines at the spin-hemisphere equator of the crust-core interface. Within the SC- $p$  superconductor (estimated to be "Type II") of the NS core magnetic field fragments into an extremely dense array of quantized flux-tubes, each containing a magnetic flux  $\Phi_0 = \pi\hbar c/e \sim 2 \cdot 10^{-7} \text{ G cm}^2$ . One such flux-tube, among the  $10^{30}$  in the interior of a typical NS, is shown in the Figure 2 cartoon. Unlike their neutron vortex line counterparts flux tubes turn and twist, a relic of a young highly conducting NS's initially complicated toroidal and poloidal magnetic fields after its violent birth. The area density of the quantized flux-tubes

$$n_\Phi = \frac{B}{\Phi_0} \sim 5 \cdot 10^{18} B_{12} \text{ cm}^{-2} \quad (2)$$

Within the non-superconducting crust the flux tubes merge into a microscopically smooth B.

MSPs are generally believed to achieve their very high spin from a surrounding accretion disk fed by a companion (still present around PSR J0437). As the NS spin-up begins and continues (typically for longer than  $10^8$  years) the original SF-n vortex array moves inward toward the NS spin-axis. The inward moving vortices must either cut through the core's magnetic flux array in which they are embedded or else carry those flux-tubes inward with them. Detailed calculations show that because of the SF-n-vortices' very slow inward velocity during this long spin-up ( $< 10^{-9}$  cm s $^{-1}$ ) the inward moving SF-n vortex array enforces a similar inward co-motion of the much denser, more flexible and complicated, flux-tube array through which it passes (Ruderman et al 1998). Because of motion-induced flux-tube bunching, such forced flux-tube co-motion would be expected even if the inward velocity of the SF-n vortices were very much faster (R 01). [In the much earlier spin-down era in the history of this NS, SF-n vortices moved outward from the NS spin-axis, carrying the core's flux tubes outward with them. There is strong supporting evidence for just such magnetic field evolution in much younger spinning-down radiopulsars (R 01)].

Figure 3 shows the expected NS surface field evolution during spin-up for three prototype initial surface field configurations. (The very long time scale for spin-up to a MSP greatly exceeds the several  $\times 10^6$  year Eddy diffusion time through the thin stellar crust. Therefore even if movement of an overstressed crust is neglected, crust conductivity is sufficient to insure that on long time scales the crust's surface field reflects that of the core surface a km. below it.) In Figure 3's case (b) flux leaving the NS's upper spin-hemisphere returns to the star in that same hemisphere. In this case prolonged spin-up of the NS must result in a dipole moment orthogonal to the NS spin-axis, positioned on that axis where it meets the core's surface (cf. also Figure 4). NS spin-up from an initial period  $P_0$  to a final  $P_1$  reduces the NS dipole moment by a factor  $(P_1/P_0)^{1/2} \sim 10^{-2}$ . It is this diminishing dipole strength that allows accretion to achieve such very strong spin-up. In Figure 3's case (a) all returning flux from the upper spin-hemisphere comes back to the stellar surface in its lower spin-hemisphere. From this initial configuration prolonged spin-up results in an aligned pulsar. Here, however, there can only be an increase in the dipole moment component parallel to the spin. Therefore such a NS could not be spun-up to a very small period MSP unless its initial dipole moment was already less than  $10^9$  G. The Figure 3 case (c) NS is nearly that of case (b). Here, however, a small fraction of the flux out of the upper spin-hemisphere returns to the stellar surface in its lower hemisphere. During stellar spin-up the large orthogonal dipole component become much smaller as in case (b), but the small aligned component is not similarly quenched. Whether, after  $P_0 \rightarrow P_1 \ll P_0$ , the strongly quenched orthogonal moment or the initially much smaller but unquenched aligned one dominates depends on both the initial field distribution and on  $P_1/P_0$ . However, when  $P_1 \ll P_0$  is achieved, high fractions of both orthogonal and aligned MSPs are expected.

#### 4. Aligned MSP polar caps and PSR J0437

Figure 4 shows details of final "spin-up squeezed" surface magnetic fields after NS spin-up to very short period MSPs. Its left panel is that for the orthogonal dipole after the pre-spin-up field configuration of Figure 3 (b). Agreement between the expected radio-emission with this left panel distribution and radio observations of the MSP orthogonal rotator PSR 1937 has been considered in CR (93). The "spin-up squeezed" structure of the surface magnetic field of an aligned pulsar is shown in the middle panel of Figure 4, and in more detail in the right panel of it. In such a MSP the surface polar cap is only a short distance (the crust thickness  $\Delta$ , about 1 km above a magnetic pole. One consequence is that the polar cap magnetic field is about  $(R/\Delta)^2$  times larger than it

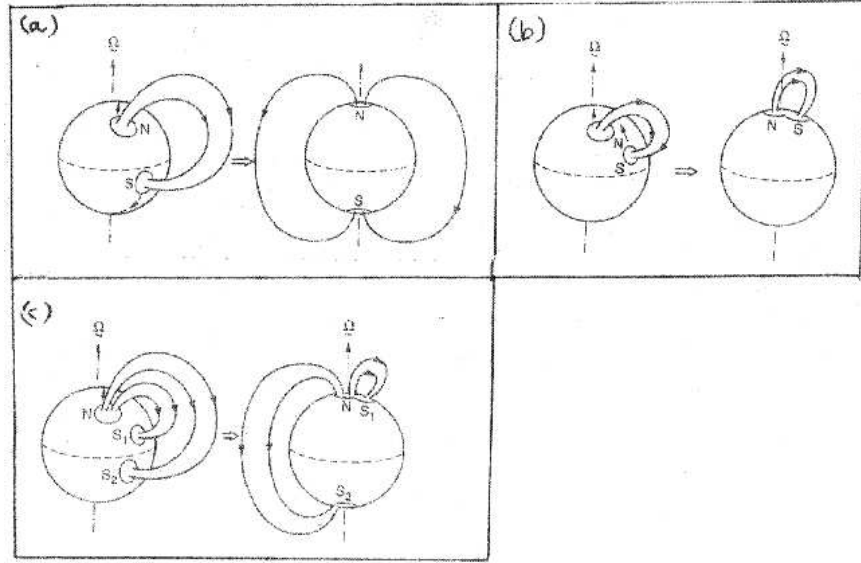


Fig. 3. Evolution of the surface magnetic field during prolonged spin-up of a neutron star. Case (a): flux-lines from the upper spin-hemisphere of the neutron star return to the stellar surface only in the lower spin hemisphere. Case (b): flux-lines from the upper spin-hemisphere return only to that same hemisphere. Case (c): an intermediate case in which some of the flux out of the upper spin-hemisphere returns to each.

in conventional NS models with the same NS dipole moment at the center of the star or from a uniformly magnetized core (CRZ 98). However, the magnetic flux through the polar cap (= the magnetic flux through the pulsar's "light cylinder") remains the same. Therefore, the polar cap radius of a strongly spun-up aligned MSP (PSR J0437 has  $P=5.75$  ms) should be

$$r_1 \sim \Delta \left( \frac{\Omega R}{c} \right)^{1/2} = 190 \left( \frac{P}{6ms} \right)^{1/2} m \quad (3)$$

rather than the canonical

$$r_{PC} = R \left( \frac{\Omega R}{c} \right)^{1/2} = 1.9 \left( \frac{P}{6ms} \right)^{1/2} km \quad (4)$$

In a very old MSP which long ago stopped accreting the main source for continuing thermal X-ray emission is expected to be from heating of its polar caps by backflow onto them of extreme relativistic  $e^-$  or  $e^+$ . These come from separated  $e^\pm$  pairs made within or above an accelerator on the open field line bundle between the polar cap and a rapidly spinning aligned MSP's light cylinder. The  $e^-$  or  $e^+$  will be funneled down along the open B-field lines onto the tiny radius  $r_1$  polar cap. [At the polar cap the energy of each such inflowing energetic lepton to the polar cap of PSR J0437 (initially acquired in the accelerator) 3 ergs, an energy not sensitive to assumptions about accelerator parameters (Wang et al 1998). The associated power inflow onto a heated polar cap is more difficult to estimate because of uncertainty about the  $e^-(e^+)$  flow rate.]

A second source of PSR J0437 surface heating is the  $10^2$  MeV curvature radiation from its 3 erg leptons as they move down curved field lines toward the polar cap. As

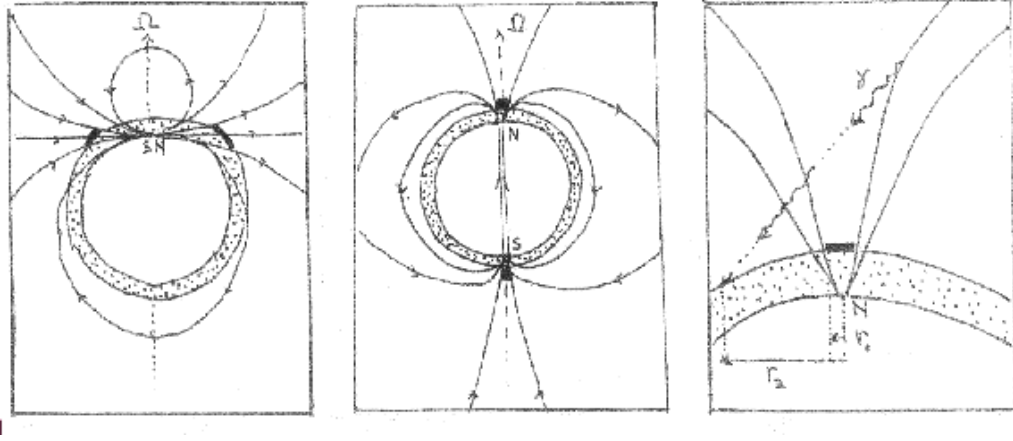


Fig. 4. Magnetic field configurations of strongly spun-up millisecond pulsars (MSPs). The left panel shows that of a spin-up squeezed orthogonal rotator. The middle panel shows the spin-up squeezed field of an aligned rotator. The right panel is a magnified view of part of the middle one near the polar cap. Indicated in it is a gamma-ray of the curvature radiation from an extreme relativistic inflowing electron (positron) moving along a curved open field line. The field line curvature and the associated curvature radiation disappear as the surface is approached.

indicated in the right panel of Figure 4, when a strongly spun-up MSP is an aligned rotator these B-field lines are so dominated by the nearby local pole as they approach the stellar surface that the guiding field lines become almost straight within a distance  $R$  of the polar cap. The inflowing leptons' curvature radiation then drops greatly when they enter that region. The curvature radiation heating of the aligned MSP's surface, which can be comparable in magnitude to that from particle flow onto its squeezed polar cap, is therefore mainly onto a large annulus of inner radius

$$r_2 \sim r_{PC} \sim 10r_1 \sim 2km \quad (5)$$

Thus an aligned PSR J3047 with the spin-up squeezed geometry of Figure 4 should emit its hottest thermal radiation from a tiny hot polar cap with the radius  $r_1$  of Equation 3 and cooler thermal radiation from a much larger surrounding annulus with an inner radius the  $r_2$  of Equation 5.

Observed soft X-ray emission from PSR J0437 fits a combination of a power law spectrum together with two black body components of almost equal luminosity (Zavlin et al 2002, Pavlov et al 2002, B&A 02). Soft X-ray power law radiation is expected from the synchrotron emission by  $e\pm$  pairs created by accelerator produced  $\gamma$ -rays. The thermal components have been interpreted as emission from a hot polar cap with a radius

$$r(hot) \sim 120m$$

with a cooler rim of radius

$$r(cool) = 2.0km$$

These two radii are roughly those of Equations 3 and 5 for the expected spin squeezed geometry (right panel of Figure 4) of an aligned PSR J0437. However, such agreement as support for this special B-field geometry is weakened because a broken power law fit to the whole soft X-ray spectrum has not been excluded. If the two black body spectra interpretation is confirmed it would be a crucial supplement to other evidence for the spin - dipole moment connection in NS evolution (R 01).

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